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LASER PROPERTIES AND EYE HAZARDS

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Models and Mechanisms of the Effects of Laser Radiation
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ABSTRACT

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OBJECTIVE

To describe laser radiation parameters and possible causative factors in eye injury.

RESULTS

The relation between laser output properties and eye injury are described. Laser eye injury data is reviewed and aspects of laser safety are discussed.

CONCLUSIONS

Laser radiation can present a hazard to the eye. Users of lasers and personnel likely to be involved in laser safety programs should be familiar with some characteristics of laser radiation and the problems of laser safety.

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LASER PROPERTIES AND EYE HAZARDS

INTRODUCTION

Eye injury is a well recognized hazard of intense visible and near infrared electromagnetic radiation (1, 2). The potential of laser radiation to produce injury to the eye was recognized at almost the outset of laser development (3, 4). Active research on laser hazards as well as on potential uses of lasers in biology and medicine has been in progress for more than five years (5, 6). As a consequence, the literature is replete with articles covering almost every aspect of the biological effects of laser radiation. It is often difficult for those not involved in the research, but interested in its findings, to interpret correctly the reported results. The profusion of specialized language, particularly that describing lasers, can cause difficulty if not understood and can produce utter confusion if misunderstood. It is recognized that optometrists may play an increasing role in assessing laser hazards and/or screening for laser injury. It is important that they, and others who seek a fuller comprehension of laser effects, hazards particularly, recognize the significant parameters of lasers that relate to hazards.

The purpose of this report is to describe the basic properties of lasers and laser radiation that are important in eye hazards. We wish also to describe how lasers affect the eye and to mention experimental injury findings and some aspects of laser safety.

LASER PARAMETERS

From a practical point of view, lasers may be considered simply as intense sources of monochromatic, optical radiation (4a). It is not pertinent to this discussion to have a detailed knowledge of the inner mechanisms of laser action, rather, it is important to know which laser parameters are significant in terms of injury and how they can vary from one laser system to another.

The important laser output parameters in relation to eye injury are:

a. Wavelength of the radiation,

b. Time properties of the laser beam, and

c. Beam geometry.

The output properties of several common laser systems, including these three, are listed in Table One (page 16). The relevance of these properties is described below:

1. Wavelength.

There are more than 700 different laser wavelengths between the near ultraviolet at 0.2358 μ (235.8 nm) and the far infrared at 377 μ (377,000 nm) (7-12). Many of these wavelengths can be produced from the same laser medium but in practice, with the exception of the ionized noble gas lasers, only one wavelength is emitted from a given laser system. The electromagnetic wavelength span in which lasers operate is several orders of magnitude greater than the visible wavelength region (yet it is still referred to as the optical region). In addition to the many basic wavelengths available, non-linear optical techniques can shift a given laser output to either shorter or longer wavelengths.

Many laser wavelengths are possible and since the transmission of the eye and absorption of light in the tissues of the eye depend on wavelength, it is an important parameter in understanding laser hazards.

The site of laser injury in the eye is dependent upon the laser wavelength because radiation must be absorbed in order to produce any change (13). The relative absorption characteristics of a given tissue determine its sensitivity to radiation at different wavelengths since a certain amount of absorbed energy is required to produce injury. Threshold exposure levels for laser eye injury thus vary with laser wavelength. Over rather narrow wavelength spans these differences are small, usually less than a factor of ten for comparable exposure times.

2. Time properties.

In addition to the number of laser wavelengths available, laser outputs can be classified in terms of their time properties or time mode of operation. There are two basic types—continuous and pulsed outputs. Pulsed lasers can be classified further into long pulse and short pulse (Q-switched) types, and into those with both high and low pulse repetition rates. Throughout the visible and infrared wavelength region it is generally accepted that the primary mechanism underlying laser injury to tissue is the fact that the radiation is absorbed and causes local heating (14). Thermal injury

mechanisms are dependent on the rate at which the energy is absorbed, thus making injury thresholds a function of the time and peak power density properties of a laser beam incident on tissue (15, 16). At low power densities and long pulse lengths, heat dissipation via thermal conduction in the tissue will limit the local temperature rise, whereas for short pulses the heat cannot escape from the site of absorption and less total absorbed energy is required to produce corresponding temperature increases, and thus injury (15-18). For a given laser wavelength and a given tissue, the threshold dose is different for continuous and pulsed exposures. Also, the threshold dose can vary for different pulse lengths, depending on the relative absorption properties of the tissue.

3. Laser beam geometry.

The radiation output from a laser is usually contained in a narrow beam. The internal optical properties of the laser and, in some cases, additional external optics, restrict the beam spread to very small divergence angles. This property of laser radiation is one of the major sources of its potential to produce injury at great distances, particularly to the retina.

Figure One (page 15) illustrates the basic geometry of laser beam divergence. The beam diverges, as stated above, with some characteristic angle θ or half angle $\theta_{\frac{1}{2}} = \frac{1}{2}\theta$. The half angle is related to the beam radius at a distance Z from the laser by:

$$\tan \theta_{\frac{1}{2}} = y/Z, \text{ or } y = Z \tan \theta_{\frac{1}{2}}$$

and R, the beam radius at Z is:

$$R = r + Z \tan \theta_{\frac{1}{2}}$$

Laser divergences are typically less than 10 mr and for small angles the tangent is approximately equal to the angle, or $R = r + Z\,\theta_{\frac{1}{2}}$.

If the laser output is pulsed and has a total energy E (or is continuous with a power output P), the energy density (power density) at a distance Z from the laser is written as:

$$E_d \text{ (or } P_d) = \frac{E \text{ (or P)}}{\pi(r + Z\,\theta_{\frac{1}{2}})^2} .$$

At large distances, $Z\theta_{\frac{1}{2}}$ is much greater than r and the equation may be approximated by:

$$E_d \text{ (or } P_d) = \frac{E \text{ (or P)}}{\pi Z^2 \theta^2_{\frac{1}{2}}} \qquad \frac{\text{joules (watts)}}{\text{unit area}}$$

It can be seen readily that this is an expression of the familiar inverse-square law.

It is the magnitude of the incident power density or energy density of a laser, operating with a given time duration, which determines whether or not an injury is produced. Thus, the output beam energy (or power), the distance to the interaction site, and the beam divergence angle are the factors that constitute the exposure conditions. In many cases, the incident power or energy density is the only factor required to determine hazardous conditions. The relation between energy and power and the various units for each are discussed in the Appendix.

It must be pointed out that we have not used common "laserology" terms such as "coherence" and "stimulated emission." Although these terms are often used when discussing lasers, they are not necessary for understanding laser hazards.

To summarize briefly, there are three basic parameters which characterize a given laser or laser system, and which are important in understanding laser eye hazards. They are:

a. Laser output wavelength. This determines the tissues of the eye that can be injured. Threshold injury doses are different for different laser wavelengths.

b. Time characteristic of the output. The threshold doses are dependent on whether the laser output is continuous or pulsed. Pulse length and pulse repetition rate are also important.

c. Beam divergence angle. This determines the amount of power density or energy density that a laser can deliver at a given distance from the system.

LASER EFFECTS ON THE EYE

1. <u>General.</u>

The transmission of the human ocular media, as a function of wavelength, has been measured by Geeraets <u>et al</u> (19) and Boettner and Wolter (20) and others. These results show that not only do substantial amounts of light in the visible region (350 nm to 750 nm) reach the retina, but that significant fractions of radiation in the near infrared, to wavelengths slightly longer than 1300 nm, are transmitted through the ocular media to the retina. At longer wavelengths, throughout the rest of the infrared, the absorption of radiation by water molecules is the dominant factor in determining the optical transmission of the eye. Since the absorption by water is very high in the infrared, radiation at these wavelengths is absorbed in the anterior segment, for the most part in the cornea (21).

Although there are laser systems that operate in the near ultraviolet portion of the spectrum (i.e., at wavelengths shorter than 350 nm), we are not including any consideration of this wavelength region. This is because, with the exceptions of the pulsed nitrogen laser at 337.1 nm, and the continuous Neon Ion laser, at 332.4 nm, ultraviolet systems at present are not generally available. Ultraviolet lasers are not in widespread use, and there have not been any studies of ultraviolet laser eye injury reported.

2. <u>Corneal injury.</u>

In the infrared region at wavelengths longer than about 1300 nm, there is only one common laser system which operates at output power levels that are distinctly hazardous. This is the CO_2 laser which can be operated either continuously or pulsed at high repetition rates. Its output is in the mid-infrared at approximately a wavelength of 10.6 μ (10,600 nm). Since this wavelength is in the region of very high absorption for water, the interaction site in the eye is the cornea and more particularly the corneal epithelium (22). Radiation at this wavelength does not penetrate to the retina, since the equivalent optical density of the ocular media at 10.6 μ is in excess of 600.

Clinically, a lesion produced by CO_2 laser radiation is a thermal burn of the cornea. The extent of injury, whether limited to the epithelium or involving the stroma to the point of corneal blistering, charring and perforation, depends on the incident dose (23), that is, the combination of power density incident on the cornea and the duration of exposure. Mild corneal burns involving only the corneal epithelium and appearing as a minimally observable change in the

epithelium, are reversible and constitute what is generally called the threshold injury (24, 25).

At doses below those required to produce clinical threshold injury there is strong evidence that a heat sensation in an irradiated cornea can give a cue to exposure (26). At low power densities, which require a relatively long exposure time to produce an injury, this heat sensation could induce a person to avoid injury by blinking or by moving. However, at high power densities, where the exposure time required to produce a lesion is equal to or less than the blink reflex time, a person cannot expect to avoid injury unless prior protective measures have been taken. Table Two (page 17) contains some experimental CO_2 laser threshold doses as reported in the literature.

3. Retinal injury.

The majority of other laser systems in widespread use operate at wavelengths in the visible and those portions of the near infrared spectrum which can affect the retina because of the transmission of the ocular media. The retinal injury from laser radiation is generally considered to be due to the heating that results from the absorption of radiation in the retinal pigment epithelium and choroid (14a, 15a, 17a, 27). At dose levels in excess of threshold, the clinical lesion can be as severe as an intraocular hemorrhage with retinal tear (28, 29). At lower dose levels, approaching threshold, the lesion is usually characterized as a white or white patchy area. Due to the focusing of the eye, lesions of the threshold variety can be very small in diameter and correspondingly difficult to observe and identify. Supra-threshold lesions, soon after exposure, have been shown to affect visual acuity and field (30).

The size of the retinal image of the laser beam plays a very large role in determining the incident dose at the cornea that is capable of producing a retinal lesion. The energy density or power density at the retina is increased over that at the entrance pupil of the eye by the optics of the eye (4b). This is due to the fact that the image formed is usually smaller than the pupillary aperture, thereby increasing the energy or power per unit area. The relation between incident energy density (or power density) at the plane of the pupil and the corresponding quantity at the retina is simply given by the inverse ratio of the respective areas. This can be written in terms of the relative diameters squared, that is:

$$\frac{E_d \text{ (pupil)}}{E_d \text{ (retina)}} = \left[\frac{D \text{ (retina)}}{D \text{ (pupil)}}\right]^2$$

where D (retina) is the image diameter at the retina, D (pupil) is the diameter of the pupil, and absorption in the ocular media has been neglected. If the eye is located far enough away from the laser source, so that the laser appears as a point source, the retinal image formed will be very small, on the order of 10 μ in diameter, essentially the point spread function (31). In such situations, the energy density magnification represented in the above equation can, with an 8 mm pupil, be as high as 600,000.

If the eye is nearer to the laser output aperture, so that the aperture no longer appears as a point source, two possibilities exist. First, if the laser beam divergence angle is less than the visual angle subtended by the output aperture at the eye, the image size on the retina is still of minimum size. Second, if the laser beam divergence angle is greater than the visual angle of the aperture, then the image on the retina is the usual one determined by ray optics for an illuminated object. In the first case, the laser beam is essentially collimated, whereas in the second case it is diverging more significantly (4c).

The large dose magnification factor, $\left[\frac{D \text{ (pupil)}}{D \text{ (retina)}}\right]^2$, is primarily responsible for the sensitivity of the eye to retinal injury from visible and near infrared laser radiation. For example, consider the case where the retinal energy density dose for threshold injury from a short pulse visible laser is 0.1 joules/cm^2. This retinal dose could be produced by an incident dose to the surface of the eye of approximately 1.6×10^{-7} joules/cm^2. A laser with an output full beam divergence angle (θ) of 2 mr (0.002 r) and a pulsed energy of 0.5 joules can produce 1.6×10^{-7} joules/cm^2 at a distance of 10,000 meters. These conditions are not significantly altered in a non-turbulent relatively clear atmosphere (32, 33).

Table One lists the output capabilities of some visible and near infrared lasers. As can be seen from this table, 0.5 joules is a relatively low output from either a Ruby or Neodymium Q-switched laser.

Table Three (page 18) lists some of the threshold doses required to produce minimum clinical injury to the retina. Most of the

reported data have been obtained using animal eyes as noted and are expressed in terms of calculated retinal energy or power density. Included in the table are corneal doses which are calculated from the experimental retinal values on a worst case basis. It must be emphasized that both sets of numbers are data calculated from the actual experimental data and are subject to many possible errors. The actual measured quantity in the experiments is the dose incident on the surface of an animal eye. The size of the retinal area exposed is measured by indirect means and the retinal doses are calculated from these two measurements. We have converted the reported retinal values to corneal values using the approximate energy density magnification factor of 600, 000. In the practical situation one is interested in protecting humans from eye injury. This requirement demands a dose that can be measured, or calculated, in terms of incident radiation on the surface of the eye. Thus, one is faced with extrapolating, by calculation, the animal results to humans, in order to obtain values useful in practice.

Precise extrapolation of animal data to humans is very complex and is beyond the scope of this report. The topic of safety factors, however, is different. Generally, an ad hoc value of 10 or 100 below the threshold for clinical injury is chosen as a safety factor (34, 35). This is probably a reasonable choice when the injury mechanism is somewhat obscure. For example, the injury mechanism in Q-switched laser retinal injury is thermal in nature, but its exact mode of operation is not yet clear (15b, 36, 37, 38). At longer exposure times, and lower power densities, retinal injury is most likely due to local tissue heating (27a, 39) and temperature dependent denaturation of proteins (15c, 40). Safety factors based on allowable temperature increases seem to be more meaningful and realistic (18a, 41, 42).

4. Injury to other portions of the eye.

There have been studies of laser injury to the lens and iris (23a, 43, 44). However, in the practical situation, neither injury appears as a significant hazard. In terms of corneal irradiance, the reported doses necessary to produce damage to the iris or lens from visible radiation are much higher, more than 100, 000 times the dose required to injure the retina (44a, 45). So, in the practical case where the entire eye is irradiated with visible or near infrared radiation, injury to the retina will occur at doses much lower than those required to injure the iris or lens.

In the mid infrared, at 10.6 μ, injury to the lens has been shown to occur. However, this occurs as a consequence of laser heating of the cornea and at doses in excess of the corneal injury threshold (23b). Thus, even in this case, lenticular damage is not a primary hazard.

SAFETY AND PROTECTIVE MEASURES

In a laboratory environment, safe laser operating procedures must be maintained. This is best accomplished through the establishment of a safety program and appropriate controls (46, 47). Outside the laboratory, safety and control procedures are even more necessary, since the chances of accidental exposure are higher.

The general common sense rule of safety with laser beams is: "Don't Look" (48). If this cannot be followed there are many safety goggles which offer varying degrees of protection at specific laser wavelengths. Table Four (page 19) contains a list of available safety eyewear and their properties.* Some of the disadvantages of present safety eyewear in addition to those noted in the table are: vision is usually reduced; the visual field is restricted; and visible laser beams become invisible when viewed through goggles, thus making their location not as readily identifiable.

SUMMARY

Laser hazards are important for laser users and those charged with safety responsibilities. We have presented a basic discussion of laser output properties in the context of eye injury. The retina is sensitive to radiation in the visible and in portions of the near infrared. The cornea is the primary site of injury from laser radiation throughout the rest of the infrared region. In terms of delivered dose, the eye is far more sensitive to visible and near infrared laser radiation than it is to radiation which is absorbed by the cornea. The optics of the eye account for this sensitivity and the result is that visible and near infrared laser radiation is the major source of laser hazards. Accidental exposure to visible laser radiation can be hazardous even at great distances from low to moderate output devices.

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* Data compiled by Mr. W. J. Schreibeis, Bell Telephone Laboratories (to be published--American Industrial Hygiene Association Journal).

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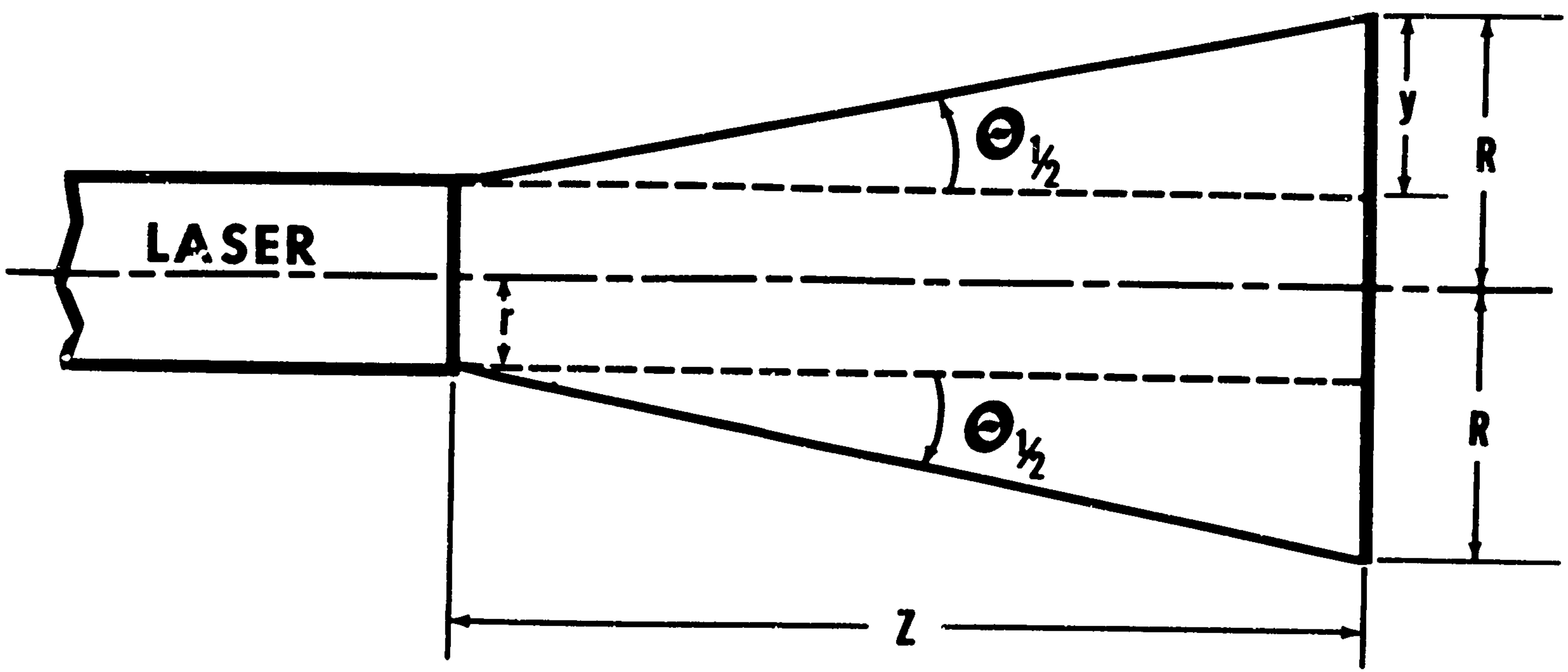

Fig. 1. Laser beam geometry.

Table One

Properties of Some Popular Lasers

Laser	Type	Wavelength In Microns	Time Properties	Typical Range of Output	Typical Beam Divergence	Remarks
Helium-Neon (He - Ne)	Gas, Atomic	0.6328	Continuous	0.5-100 mwatts*	1 mr**	Has two strong IR lines at 1.15, 3.39μ
Ruby	Solid, Crystalline	0.6934	Continuous Long-Pulse Q-Switched	0.1-10 watts 0.1-300 joules 0.1-30 joules	2 mr 5-10 mr	Historically the first laser Still widely used
Neodymium In Glass	Solid, Glass	1.06	Long Pulse Q-Switched	0.5-1000 joules 0.1-60 joules	2-10 mr	More efficient than Ruby (0.5% - 1%)
Neodymium in Yttrium-Aluminum Garnet (YAG)	Solid, Crystalline	1.06	Continuous Q-Switched High Rep. rate	0.5-50 watts 0.08-0.5 joules 1 watt average power	2-5 mr	
Argon	Gas, Ionized	0.488	Continuous High Rep. rate	0.1-10 watts 0.1 watts average power	1 mr	Has many lines
Krypton	Gas, Ionized	0.6475	Continuous	0.1-2 watts	1 mr	Can produce several lines simultaneously "White laser light"
Carbon Dioxide	Gas, Molecular	10.6	Continuous High Rep. rate	1-2500 watts 1-500 watts average power	1 mr	Efficiencies as high as 30%
Gallium-Arsenide (GaAs)	Semiconductor	0.84-0.9	Continuous High Rep. rate	0.01-2 watts Very low average power	500 mr	High efficiencies must be cooled to obtain high power outputs

* Milliwatt.

** Milliradian (1 Radian = 57.3°)

Table Two

Corneal Effect Thresholds at 10.6 microns *

Observer	Exposure Time (seconds)	Power density (watts/cm^2)	Remarks
Feigen [50]	30	0.1	No change observed at this dose
Zweng [51]	0.055	18	Minimal clinical change
"	0.010	61	" "
"	0.0035	125	" "
Gullberg [26]	10	0.24	Change in blink reflex, no observable injury
"	1	0.75	" " "
"	0.1	2.4	" " "
"	0.01	7.5	" " "

* All reported studies use rabbits as the experimental animal.

Table Three

Reported Retinal Injury Thresholds

Observer	Laser	Exposure Time (seconds)	Reported Retinal Dose	Approximate Corneal Dose For Humans	Experimental Animal
Geeraets[28]	Ruby Q-Switched	30×10^{-9}	0.07 j/cm^2	1.2×10^{-7} j/cm^2	Rabbit
Geeraets[28]	Ruby	0.2×10^{-3}	0.72 j/cm^2	1.2×10^{-6} j/cm^2	Rabbit
Jones[29]	Ruby	1.5×10^{-3}	3 j/cm^2	5×10^{-6} j/cm^2	Monkey
Vassiliadis[24]	Ruby Q-Switched	8×10^{-9}	1.6 j/cm^2	2.7×10^{-6} j/cm^2	Human
Vassiliadis[24]	Ruby Q-Switched	8×10^{-9}	0.1 j/cm^2	1.7×10^{-7} j/cm^2	Rabbit
Vassiliadis[24]	Ruby Q-Switched	8×10^{-9}	0.8 j/cm^2	1.3×10^{-6} j/cm^2	Monkey
Zweng[51]*	Neodymium	10^{-3}	- - - -	4.5×10^{-4} j/cm^2	Monkey
Zweng[51]	Neodymium Q-Switched	30×10^{-9}	- - - -	2.8×10^{-5} j/cm^2	Monkey
Zweng[51]	Argon	0.1	- - - -	2×10^{-3} watts/cm^2	Monkey
Kohtiao[49]	Helium-Neon	2.5	0.5 watts/cm^2	1×10^{-4} watts/cm^2	Rabbit

* Data given as corneal dose for a 7 mm pupil diameter.

TABLE 4

LASER EYE PROTECTION GOGGLES

Based on Manufacturers' Information

OPTICAL DENSITY = $\log_{10} \frac{1}{\text{Transmittance}}$

Manufacturer or Supplier	Catalogue Number	Argon 4880 Å	HeNe 6328 Å	Ruby 6943 Å	GaAs 8400 Å	Nd 10600 Å	CO_2 10.6μ	UV Protection	Approx. Cost $	No. of filters & thickness of each	Visible light trans-mission
American Optical Co.	SCS-437	.05	.05	0.5	2	4.5	High	No	55	1, 3.5mm	90 %
	580, 586*	0.2	2+	3.5	4	2.7	-	Yes	35, 25*	1, 3.5mm	27.5 %
	581, 587*	0.6	4.1	6.1	5.5	3	-	Yes	35, 25*	1, 3.5mm	9.6 %
	584	0	1	5.0	13.5	10.9	High	Yes	55	2, 2mm	46.0 %
	585	0.3	2	8.0	21.0	17.1	High	Yes	55	2, 2mm	35.0 %
	598*	13.5	0	0	0	-	-	Yes	25*	1, 3mm	23.7 %
	599	11.4	0	0	0	-	-	Yes	35	1, 2.5mm	24.7 %
	680	0	0	0	0	0	50	No	35	1, 2.75mm	100 %
Bausch & Lomb	5W3754	15	0.2	0	0	0	≥ 35	Yes	39	1, 7.9mm	4.3 %
	5W3755	4	0	0	0	0.1	≥ 35	Yes	39	1, 7.9mm	57.0 %
	5W3756	0.8	12.2	15.5	5.6	4.8	≥ 35	Yes	39	1, 6.4mm	6.2 %
	5W3757	0.9	4.5	7.7	11.8	5.7	≥ 35	Yes	39	1, 7.1mm	
	5W3758	1.9	1.8	2.2	4.8	7.5	> 35	Yes	39	1, 7.6mm	3.0 %
Control Data Corp.	TRG-112			10+					50	1,	
Fish-Schurman Corp.	FS650AL/18	2.7	6.0	10	<10	<10		No	48	1, 6mm	50.0 %
Spectrolab		5	5	9	18	13	3	Yes	95	2, 3.2mm	25.0 %

*Spectacle Type

CAUTION

1. Goggles are not to be used for viewing of laser beam. The eye protective device must be designed for the specific laser in use.
2. Retinal and corneal thresholds of damage are still under investigation.
3. Optical density values may vary somewhat from those reported by the manufacturers.
4. Few reliable data are available on the energy densities required to cause physical failure of the eye protective devices.
5. The establishment of engineering controls and appropriate operating procedures should take precedence over the use of eye protective devices.
6. The hazard associated with each laser depends upon many factors, such as output power, beam divergence, wavelength, pupil diameter, specular or diffuse reflection from surfaces, etc.

APPENDIX

Power and Energy

The total output energy, per pulse, of a pulsed laser is usually given in joules, while the output power of continuous lasers is given in watts. There are fundamental relationships between the units of energy and power, and there are several unit systems used for each.

Basically, energy is a measure of work, that is, the equivalent of a force acting through a distance. In terms of thermal energy, heat is a measure of work. The unit of thermal energy in centimeter, gram, second (cgs), units is the gram-calorie or calorie. The corresponding unit of mechanical or radiant energy, in cgs units, is the erg, and, in mks (meter, kilogram, second) units, the joule or watt-second. The conversion factors relating these different units are:

1 calorie = 4.18 joules

1 joule = 10^7 ergs

Power is the rate at which work is done. Mathematically, this is written as:

$$P = \frac{dE}{dt} \tag{1}$$

$$\text{or } E = \int_0^t P \, dt \tag{2}$$

In the simplified case, where the power is not an explicit function of time, that is, when the power is a constant, the latter equation may be written as:

$$E = P\, t \tag{3}$$

The mks unit for power is the watt. Thus, a continuous laser operating at 10 watts constant power output will deliver an output energy of 1 joule in 0.1 seconds, 10 joules in 1 second, 100 joules in 10 seconds, etc.

On the other hand, a pulsed laser output is described in terms of energy in a pulse. An output pulse of energy E and length t has a maximum rate of energy output or peak power output given approximately by:

(4) $$P = E/t$$

The assumption is made that the pulse is flat-topped, that is, that the output power is constant during the pulse. Thus, a 1 joule laser pulse with a 1 millisecond pulse length has an approximate peak power of 10^3 watts, whereas a 1 joule pulse of 10^{-8} seconds pulse length has a peak power of 10^8 watts or 100 megawatts.

The average power output of a continuous laser is obviously equal to its constant power output. The average power output of a pulsed laser on the other hand, depends on the number of pulses per second, or the pulse repetition rate. Thus, a pulsed laser of 1 joule output with a pulse repetition rate of one pulse per second has an average power output of 1 watt, irrespective of the pulse length.

The conversion factors for different units of power are identical to those for energy, that is:

1 calorie/sec = 4.18 watts

1 watt = 10^7 ergs/sec

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13. ABSTRACT

Eye injury is a recognized hazard of laser radiation. This report includes a basic discussion of those laser output parameters that are important in understanding lasers and how they are related to laser eye injury. The three most significant properties of laser beams in this respect are wavelength, time characteristics and beam geometry. The first two determine the site most susceptible to injury and its sensitivity to laser exposure dose. The third, beam geometry, essentially governs the distance at which a given laser is capable of producing a hazardous exposure condition. A brief description of experimental injury findings and some threshold exposure doses, as reported in the literature, are summarized. Laser safety considerations are discussed. (U)

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